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ELECTRICAL MODEL OF PISCINE ELECTROSENSING SYSTEM. MODEL SIMULA--ETC(U)
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Technical Report 806

ELECTRICAL MODEL OF PISCINE ELECTROSENSING SYSTEM

Model simulates responses of certain fish to both uniform and short-range electric fields

CS Johnson

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This report describes a model of a piscine electrosensing system. A threshold sensitivity of 10^{-5} V/cm was obtained. Electrode variations and noise were the limiting factors in model performance.

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OBJECTIVE

Create and test an electrical model of a piscine electromagnetic sensory system.

RESULTS

1. Laboratory tests of the responses of the model to artificially produced electric fields duplicated some of the responses expected from fish in similar conditions.

2. With uniform fields, color and brightness distributions on the display associated with the model indicated correctly the direction and intensity of the applied fields.

3. "Short range" dipole fields, in which field intensity decreases inversely with the cube of the distance from the sensors, produced responses from only one or two sensors at short range, with the color of the display indicating the orientation of the electric dipole.

4. Sensitivity thresholds of the model, found to be limited by electrode (electrochemical) and electronic (electrothermal) noise, varied continuously from about 10^{-4} to 10^{-5} V/cm.

5. The model lacked by at least an order of magnitude the 10^{-6} V/cm sensitivity that would be required to detect the earth's magnetic field.

RECOMMENDATIONS

1. Develop stable low-noise electrodes before attempting to model more closely the piscine electrosensing system.

2. For future models, employ low-noise electronics and solid-state relays throughout.

INTRODUCTION

Many species of fish have special sensory systems whose primary purpose is to detect electromagnetic fields. These systems contain the most sensitive electromagnetic detectors yet discovered in the animal world. Because of their extreme sensitivity, an understanding of their mode of operation has the potential of leading to applications of interest to the Navy. Experiments with trained sharks and rays have been conducted for several years at NOSC and at other laboratories outside the Navy. Enough information has been obtained to permit modeling of the electromagnetic sensory systems of fish. This report describes one model and the results of tests with it.

ELECTRORECEPTION BY FISH

Dijkgraaf (ref 1) showed that electric fields were detected by fish by means of a multitude of special ampullar organs distributed over their bodies. These organs are called the ampullae of Lorenzini. The ampullae contain cells that detect electric fields and are connected to tiny pores in the skin by tubes. These tubes have highly resistive walls and are filled with a very conductive jellylike material. A good description of the fish electroreception system is given by Satorius (ref 2).

Sharks and rays are known to be extremely sensitive to electric fields, and Kalmijn (ref 3) showed that they can detect electric fields as slight as 5×10^{-9} V/cm as well as sense field direction. They have also demonstrated the ability to detect the earth's magnetic field (ref 4). They do this by detecting the electric fields induced in their sensors as they swim through it.

MODEL DESCRIPTION

ELECTRODES

Murry (ref 5) showed that with no field present, the nerves connecting individual electrodes fire at about 30 pulses per second. If the voltage near the opening of the tube leading to an ampulla is positive relative to some distant ground, the firing rate decreases; if it is negative, the rate increases. The firing rate in either case returns to the no-voltage rate with a time constant of a few seconds. The response of the electroreceptive system also depends on the length of the tubes connecting the ampullae to the surface of the skin (Waltman, ref 6).

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[1] Dijkgraaf, S. Electroreception in Catfish, *Amiurus nebulosus*, Experientia (Basel), vol 24, p 187–188, 1968

[2] NOSC Report NUC TP 504, Electromagnetic Fields in the Ocean and Electroreceptive Fish, by EH Satorius, February 1976

[3] Kalmijn, AJ, The Detection of Electric Fields from Inanimate and Animate Sources Other than Electric Organs, chap 5 in Handbook of Sensory Physiology III, A Fessard, ed, Springer-Verlag, New York, 1974.

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[5] Murray, RW, The Ampullae of Lorenzini, chap 4 in Handbook of Sensory Physiology III, A Fessard, ed, Springer-Verlag, New York, 1974.

[6] Waltman, B, Electrical Properties and Fine Structure of the Ampullary Canals of Lorenzini, Acta Physiol Scand, vol 66, suppl 264, p 1–60, 1966.

Producing satisfactory electrodes proved to be the most difficult part of this project. The problem is that metals in contact with seawater become electrodes in which potentials as high as a few millivolts are generated. The potentials vary from electrode to electrode and with time and temperature. The most satisfactory electrodes tested consisted of plastic tubes (4-mm inner diameter), filled to a depth of 2 cm with a conductive epoxy having a resistivity of 3×10^{-4} Ω-cm.* Electrical connection to the epoxy was made by soldering the leads to 1-mm diameter by 1-cm long gold-plated pins, which were then embedded in the soft epoxy and allowed to harden.

The tubes were filled with a conductive jell made of a mixture of seawater and 2% by weight of agar of the type used in microbiological culture media.**

The electrodes performed in an unexpected way. The conductivity of the epoxy was constant when connected to wires in air; but when the epoxy was in contact with sea water, its conductivity decreased exponentially with time. There were two components to this decay, expressed by the following equation:

$$Y = (0.9 \pm 0.2)e^{-(2.6 \pm 0.4)t} + (0.1 \pm 0.2)e^{-(17 \pm 3)t}, \qquad (1)$$

where Y is relative amplitude and t is time in seconds.

The reason for this effect is not known but is apparently of electrochemical origin, because the time constants did not depend on the length of the electrode tube. Eq (1) was measured with a 30-cm tube. For a 15-cm tube, the following result was obtained:

$$Y = (0.8 \pm 0.1)e^{-(2.9 \pm 0.2)t} + (0.2 \pm 0.3)e^{-(17 \pm 6)t}. \qquad (2)$$

If the decay in conductivity were due to a capacitive effect, the RC time constant would be expected to decrease by a factor of two. While these electrodes did not produce the known electrical properties of the piscine system (ref 6), they did produce a time response about equal to that observed (ref 5). They also had the property that when they were placed in seawater and thus effectively shorted together for a few days, they all came to nearly the same potential, greatly reducing further effects of voltage differences of electrochemical origin.

A model was constructed of ten electrodes mounted on a 6-mm PVC sheet in the shape of a ray (fig 1) and attached to a 60-mm OD PVC pipe positioned at right angles to the PVC sheet. A second 33-mm OD PVC pipe was positioned aft of the 60-mm one to provide a handle for positioning this apparatus. A water depth of 100 mm was used so that the electrical connections to the electrodes would be well above the surface. For added protection, the electrode connections were coated with Plasti-Dip.*** A rectangular plastic tank 0.6 × 0.3 m was used for all measurements.

ELECTRICAL CIRCUITS

Figure 2 is a diagram of the circuits used. About 3 m of coaxial cable connected each electrode to the electronic circuits. To reduce electrical pickup along the cable, common-mode rejection was used with the PAR (Princeton Applied Research) model 113 preamplifier. The two most distant electrodes were used for the indifferent electrode and ground (electrodes 9 and 10, respectively). The shields of all the cables were grounded together at both ends electrode and chassis.

*Polycon 7000, available at AF Yale Enterprises, San Diego, California.

**Bacto-Agar, DIFCO Laboratories, Detroit, Michigan.

***Plasti-Dip International, St Paul, Minnesota.

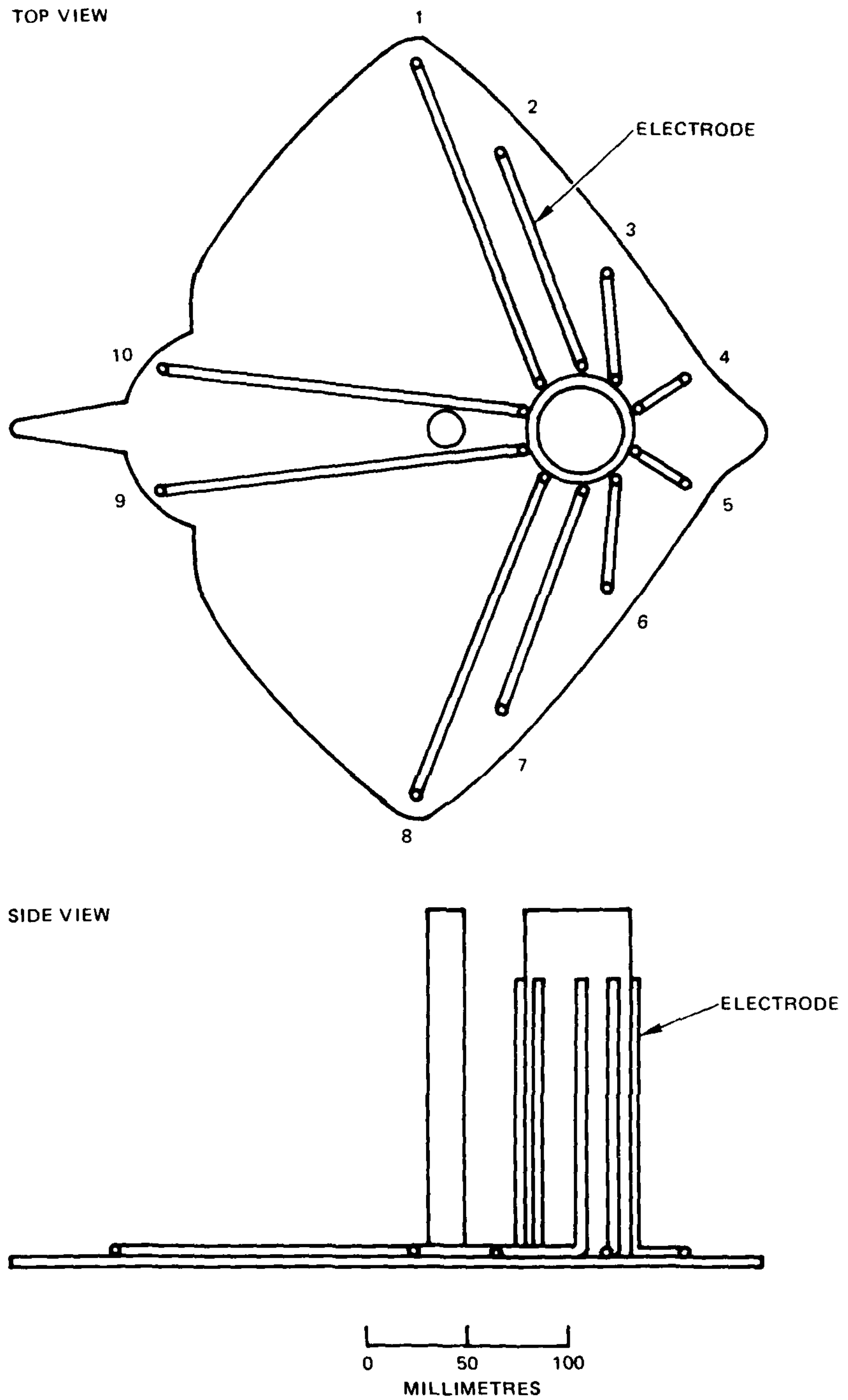

Figure 1. Top and side views of electrode placement on the ray-shaped plastic plate and around a stand-up plastic pipe. The smaller plastic pipe was used as a handle for positioning the electrode array. The electrodes were connected to coaxial cables, not shown, at their upper ends.

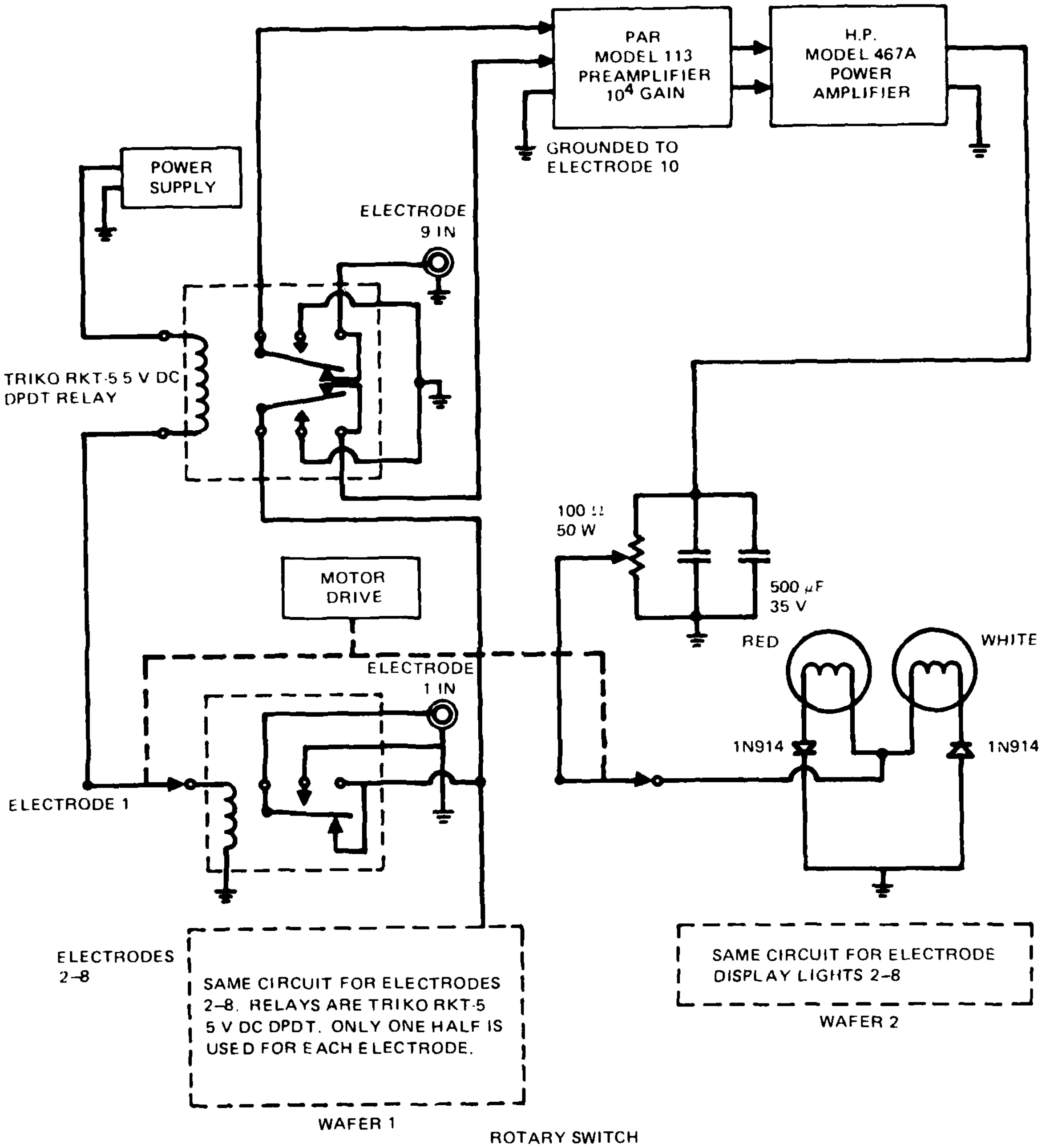

Figure 2. Diagram of the electrical circuits used. The rotary switch was driven by a 1/50 horsepower (~15 W) Bodine Electric Company fractional horsepower gearmotor with variable speed control.

Ideally eight preamplifiers would have been used to operate the model, one for each active electrode; but since only one was available, the following switching scheme was used. Eight poles were used of a motor-driven Centralab single-throw, 12-pole switch with two wafers.

One wafer was used to connect each electrode in turn to the preamplifier. The motor rotated the switch at one revolution per second, and each contact made in turn energized the coil of one of eight double-pole double-throw relays.* Through the eight relay contacts and relays each electrode was connected to the preamplifier for about 0.1 s. Only one half of each DPDT relay was used. In the normally open relay positions the electrodes were connected to ground. A ninth relay, whose winding was in series with each of the others as they were energized, switched the indifferent electrode (9) from ground to the preamplifier. Half of the DPDT relay did this. The other half grounded the signal line to the preamplifier to prevent 60-Hz pickup at intervals between switching contacts of the rotary switch. Grounding the electrodes together prevented their assuming large electrochemical potentials.

The second wafer of the rotating switch was used to operate the display, whose circuit diagram is also shown in figure 2. The display consisted of a second plastic sheet identical in shape and size to that used to hold the electrodes (fig 1). At positions identical to the distal-end locations of electrodes 1 through 8 two holes were drilled side by side. In one hole a red and in the other a white miniature 5-V Christmas tree light was mounted. The display was mounted vertically, with electrodes 4 and 5 at the top, on the electrical circuit chassis. Signals from the preamplifier were fed to a Hewlett-Packard model 467A 10-W amplifier and through a rheostat, which was used to adjust the output from the amplifier. The large capacitors were needed to eliminate unwanted voltage spikes produced during switching and relay operations. The amplified dc signals then were fed through the second wafer of the rotary switch to the lights representing the corresponding electrode. Diodes in series with the light bulbs caused the red light to shine if a positive signal was present at an electrode, the white light if a negative one was present. The brightness of the light's flash was proportional to the signal present.

RESULTS

The model was tested with uniform electric fields, such as would be experienced by fish in the natural environment, and with electric dipole fields. Dipole fields are very similar to the fields produced by natural prey, such as crabs buried in the sand, which the fish hunt by means of their electric sensors. In general the model performed as expected to both types of fields. With uniform fields, color and brightness distributions on the display indicated correctly the direction and intensity of the applied fields. "Short range" dipole fields, in which field intensity decreases inversely with the cube of the distance from the sensors (see ref 2), produced responses from only one or two sensors at short range, with the color of the light indicating the orientation of the electric dipole.

The model was intended to show general qualitative effects, but a threshold for electric field detection could be found by increasing a uniform field until the lights of the display were just visible in a darkened room. The highest sensitivity recorded (10^{-5} V/cm) was attained by using electrodes 4 and 5 — those most distant from the ground electrode (10). Sensitivity was found to be limited by electrode and electronic noise. Sensitivity thresholds varied continuously from about 10^{-4} to 10^{-5} V/cm as the result of electrode instabilities.

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*TRIKO, RKT-5 5 V dc DPDT miniature relays.

Unfortunately the threshold sensitivity was not great enough to detect the earth's magnetic field by moving the electrode array so as to induce electric potentials between the electrodes. With the present threshold sensitivity (10^{-5} V/cm) the array would have to be moved at more than 13 m/s to detect the earth's magnetic field, a speed that is not practical for laboratory demonstrations. This is unfortunate because rays are believed to use the horizontal component of the earth's magnetic field in sensing compass directions and the vertical component in sensing speed and acceleration.

CONCLUSIONS

This report describes an electrical model of the piscine electromagnetic detection system. Laboratory tests of the responses of the model to artificially produced electric fields duplicated some of the responses expected from fish in similar conditions. The model was limited in that it lacked by at least an order of magnitude the 10^{-6} V/cm sensitivity that would be required to detect the earth's magnetic field. Its detection sensitivity threshold was limited by electrode (electrochemical) and electronic (electrothermal) noise.

SUGGESTIONS FOR FURTHER WORK

Before further attempts at modeling the piscine electrosensing system are made, it is essential that stable low-noise electrodes be developed. While it was not an important factor for the current model, future models should use low-noise electronics and solid-state relays throughout.

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[1] Dijkgraaf, S, Electroreception in Catfish, *Amiurus nebulosus*, Experientia (Basel), vol 24, p 187–188, 1968.

[2] NOSC Report NUC TP 504, Electromagnetic Fields in the Ocean and Electroreceptive Fish, by FH Satorius, February 1976.

[3] Kalmijn, AJ, The Detection of Electric Fields from Inanimate and Animate Sources Other than Electric Organs, chap 5 in Handbook of Sensory Physiology III, A Fessard, ed, Springer-Verlag, New York, 1974.

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